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RECENT DEVELOPMENTS IN THE PREVENTION AND CONTROL OF SPONTANEOUS COMBUSTION IN COAL MINING OPERATIONS

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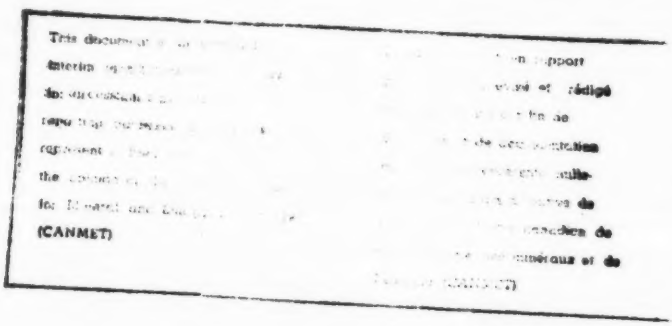

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RECENT DEVELOPMENTS IN THE PREVENTION AND CONTROL OF SPONTANEOUS COMBUSTION IN COAL MINING OPERATIONS

by

R.N. Chakravorty* and R.J. Kolada**

ABSTRACT

Spontaneous combustion presents a very serious hazard to both safety and economics of mining operations. Notwithstanding considerable research that has been done over the years to prevent and control spontaneous combustion the risk still exists. Consequently, this problem poses a major challenge to mine safety researchers; new and improved techniques are constantly being developed to deal with this major hazard.

This paper reviews the current practices to prevent and control spontaneous combustion in coal mine operations highlighting new developments in this area. Research and development work presently being carried out in Canada to deal with this problem is also discussed which includes monitoring, inertization and application of biotechnology.

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MISE AU POINT DE NOUVELLES TECHNIQUES DE PRÉVENTION ET DE CONTRÔLE DE L'INFLAMMATION SPONTANÉE DANS LES INSTALLATIONS MINIÈRES

par

R.N. Chakravorty* et R.J. Kolada**

RÉSUMÉ

L'inflammation spontanée présente un danger réel pour la sécurité des mineurs et nuit à la rentabilité des travaux d'exploitation minière. Bien que d'importantes activités de recherche aient été effectuées durant plusieurs années en vue de mettre au point des techniques de prévention et de contrôle de l'inflammation spontanée, le danger est toujours présent. Par conséquent, ce problème constitue un défi majeur que les chercheurs doivent relever pour assurer la sécurité des travailleurs dans les mines. Ils doivent constamment améliorer les techniques existantes ou en mettre au point de nouvelles, pour contrer les dangers inhérents à l'inflammation spontanée.

Le présent document porte sur les méthodes courantes de prévention et de contrôle de l'inflammation spontanée dans les installations minières et met en lumière les nouveaux développements dans ce domaine. Les travaux de recherche et développement présentemment en cours au Canada en vue de résoudre ce problème, notamment la surveillance, l'inertage et les applications biotechnologiques, sont également présentés.

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INTRODUCTION

Spontaneous combustion has always been recognized as a major hazard both from safety aspects and from economic considerations. A recent survey by Olaf [1979] has indicated that 80% of the fires in coal mining operations are caused by spontaneous combustion.

Modern mining methods demand a high capital investment. As a result the closure of a working face may involve a huge loss. Even a short interruption to production may prove very expensive. Spontaneous combustion may also produce lethal amounts of carbon monoxide in the mine air thus posing a serious threat to the health and safety of miners underground.

The world-wide recession in the early eighties resulted in a number of mine closures and production cutbacks so that large stockpiles at mine sites are common and unavoidable. Experience has shown that fires in stockpiles are difficult to extinguish. This has resulted in renewed interest in the development and application of techniques for greater control of spontaneous combustion.

Research in many countries has led to the improvement of control methods but the risk still exists. This presentation is made with a view to assist coal operators in their effort toward prevention and control of hazards due to spontaneous combustion.

CRITICAL FACTORS INFLUENCING SPONTANEOUS COMBUSTION

There is no simple method by which it is possible to predict whether a particular method of mining applied to a specific coal seam will result in spontaneous combustion. Under favourable conditions of heat accumulation, spontaneous combustion can occur with any type of coal.

It is known that sub-bituminous coals are more susceptible compared to low volatile bituminous coals, and that a high ratio of Exinite increases the risk. However, the inherent moisture content of the coal and the exposed surface area may be more significant. In addition, the actual mining and ventilation conditions strongly influence susceptibility. In practice, the experience gained with the mining method applied to a particular type of coal seam must be carefully evaluated with respect to the factors responsible for the onset of spontaneous combustion.

Feng, Chakravorty and Cochrane [1973] summarized the critical factors influencing spontaneous combustion in coal mines as shown in Table 1. Where a number of these conditions exist the mine will naturally be at a greater risk.

TABLE 1—CRITICAL FACTORS CONTRIBUTING TO SPONTANEOUS COMBUSTION

Intrinsic factors which cannot be controlled		Extrinsic factors which can be controlled
Coal properties	Geological features	Mining practices
a. High volatile matter	a. Thick seams	a. Accumulation of fine coal in worked out areas
b. High moisture	b. Presence of inferior pyrite bands and carbonaceous shale	b. Leaving roof and floor coal during mining
c. High pyrite	c. Presence of faults	c. Poor maintenance of roadways and old districts
d. High exinite	d. Weak and disturbed strata conditions	d. Inadequate measures to prevent air leakage through air crossings, doors, gateside pack
e. High friability	e. High strata temperature	e. Caving to surface under shallow overburden
		f. Multi-seam working close proximity
		g. Poor ventilation management

PREVENTION METHODS AND STRATEGIES

Mine layout is the single most important factor for the prevention of spontaneous heating. Working districts should be designed so that a particular section can be isolated at short notice without affecting production in others. Sites for preparatory seals should be identified and marked during planning. With coal seams which are highly susceptible to spontaneous combustion the retreat method of working is preferred. This is because the gob is not subjected to a large difference in ventilation pressure. Coal pillars should be designed so that they are capable of resisting excessive crush. The panel system of working is preferred particularly for mining coals susceptible to spontaneous heating. The size of each panel is calculated based on the incubation period and the rate of extraction.

Control of air leakage is of paramount importance for controlling spontaneous combustion. This is usually achieved by minimizing ventilation pressure difference, proper siting of doors, and by avoiding unnecessary stopping and starting of fans. Air leakage is also reduced by sealant coating, injection of cements in cracks and crevices and by maintaining good gateside packs.

Application of inhibitors for the control of spontaneous combustion met with limited success. Chamberlain and Hall [1973] concluded from their study that borate solution or Montan powder sprayed in the gob area or infused into a lov rank coal would reduce the possibility of spontaneous combustion.

EARLY DETECTION OF HEATING

The most practical and effective method to control heating or fire is by early detection. It is common sense that by detecting a fire at an early stage considerable loss and damage can be prevented in a mining operation. Hence it is imperative to develop methods for early detection of heatings and significant research is being conducted worldwide to achieve this.

It is generally considered that monitoring of combustion products during the early stage of heating is the most suitable method for detecting the onset of spontaneous combustion. The major gaseous products resulting from lov temperature oxidation of coal are carbon dioxide, carbon monoxide and water vapour. In mining operations carbon dioxide monitoring is considered unsuitable as there are sources other than spontaneous heating from which this gas may originate. However, carbon monoxide has proved to be a more specific product of combustion during lov temperature oxidation of coal. Over the years many heatings have been detected using the Graham's method based on carbon monoxide/oxygen deficiency ratio. A rising trend in the Graham ratio invariably indicates the onset of heating. Tashiro et al [1971] observed that monitoring of carbon monoxide alone to determine the on-set of heating is not as reliable as monitoring carbon monoxide and ethylene together. Their work further established that an increase in ethylene and alkane ratio (CH_4 /C_4H_{10}) in mine air are better indicators than an increasing trend in the carbon monoxide alone.

Continuous monitoring as opposed to spot analysis provides an opportunity for studying the trend of a particular gas produced during onset of spontaneous combustion. Chamberlain [1973] observed that for early detection of spontaneous combustion, monitoring of carbon monoxide and the correct interpretation of the data obtained, can provide a very reliable method of early warning. This also eliminates the need for analysis of

other gases such as oxygen and nitrogen. CANMET studies [1978] also indicated similar findings as shown in Figure 1. It was observed that carbon monoxide is produced in detectable amounts even at a temperature of 70°C. Hydrogen and ethane could be detected at an approximate temperature of 100°C and ethylene and acetylene was noticed in the product gases over a temperature of 150°C.

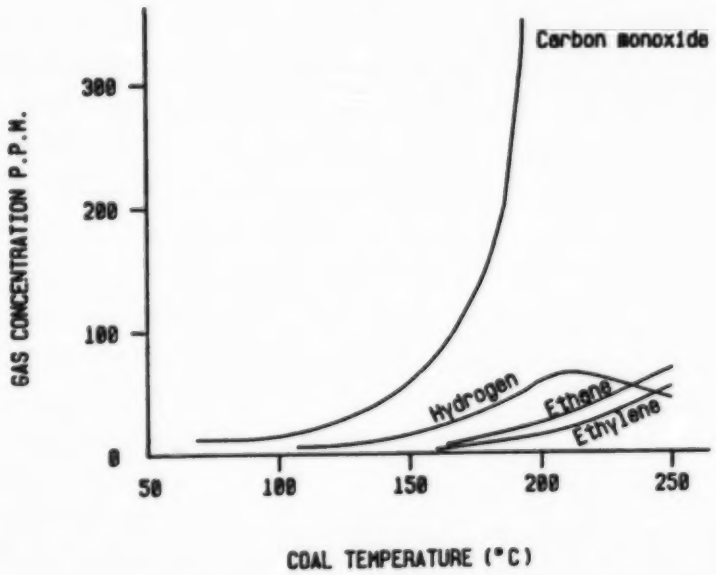
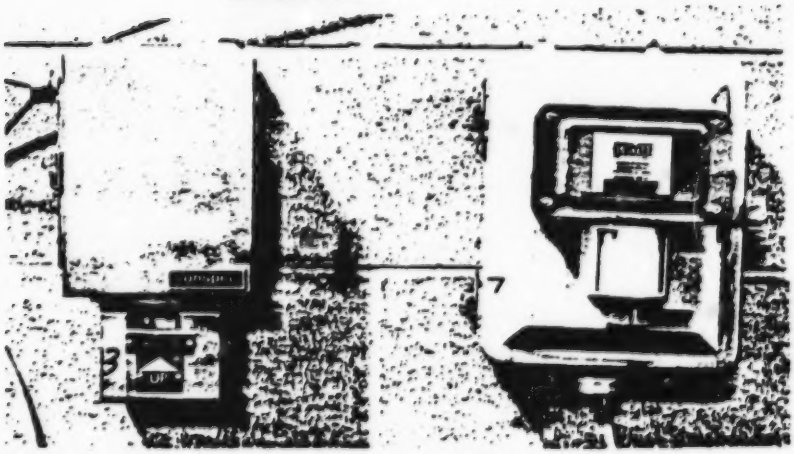


Fig. 1 - Graphs showing variations in gas concentrations with changes in temperature.

There are two main types of ventilation monitoring systems commonly used, namely the tube bundle and the telemetry system. The tube bundle system draws air from strategic locations through individual tubes. The tubes are connected to a central laboratory on the surface where the mine air is analysed for carbon dioxide, carbon monoxide, methane, oxygen etc. In comparison the telemetry system utilizes sensors which are positioned underground at strategic locations and provides an immediate analysis of the air. The information from the transducers is passed on to an outstation which has the capability of analogue to digital conversion, multiplexing,

signal conditioning and buffering for storing the data. When commanded by the computer, the outstation will transmit the stored data through the connecting cable to the central computer located at the mine surface for processing when required. The transmission of data by telemetry is virtually instantaneous whereas with tube bundle system the time between drawing a sample from a particular location and analysis at the surface laboratory often exceeds 20 to 30 minutes. Because of this time delay tube bundle systems are gradually being replaced by telemetry systems. A typical monitoring system based on telemetry is shown in Figure 2.

CRT, data printers and the processor unit



Carbon monoxide and methane sensors

Fig. 2 - Coal mine environmental monitoring system.

The major advantages of automated monitoring systems arise because of the capability of the computer to process large quantities of data, indicate when alarm levels are reached, provide shift reports and trend analysis. All these functions can be achieved with very few man hours assigned to this work. The continuous monitoring of air in underground mining operations can present a complete picture of conditions at all times and thereby enables the management to ascertain actual condition within the mine during weekends or when the mine is left idle for unavoidable reasons.

Experience in underground Canadian coal mining operations has established beyond doubt that these systems are extremely valuable both for early detection of heating and to ensure safer working environment. Figure 3 shows variations in carbon monoxide concentration in the return air. Graph A shows normal variations and graph B shows variations during the onset of a heating. [1985].

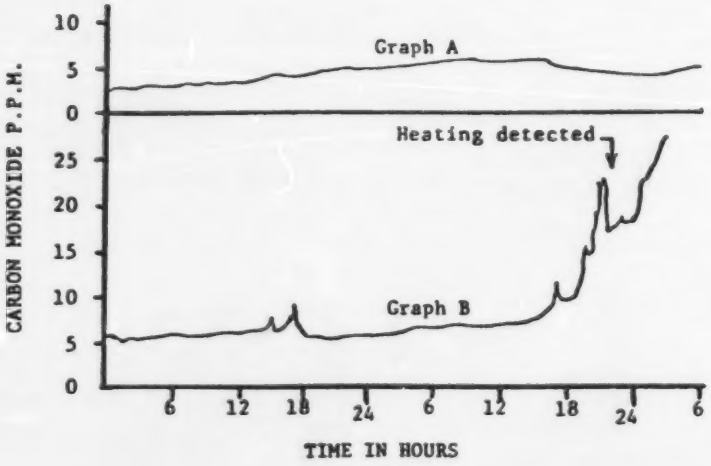


Fig. 3 - Graphs shoving variations in CO concentrations in the return air. Graph A shovs normal variations and Graph B shovs variation during onset of heating.

THERMAL METHODS

It has been noticed that the heat produced during early stages of oxidation precedes any product of combustion. Infrared scanners and thermometers have proved useful in locating hot spots in coal stacks and in underground coal mines. The infrared instruments are portable, easy to use, capable of remote measurement, and thus eliminates large scale instrumentation using thermistors and thermocouples. Most instruments are provided with telescopic sights which aids in pinpointing hot spots during thermal surveys. Infrared images can present a detailed thermal picture of the entire scene within the field of view of the instrument. It is thus capable of locating hot spots with remarkable speed and accuracy.

Considerable progress has been made in infrared technology by the introduction of recording video cameras and computer based interpretation of thermal pictures. The computer can draw trends, calculate the rate of temperature increase and include many other options in the presentation and analysis of data. Results obtained during field surveys can be analysed in the laboratory and where necessary, a micro-computer can be interfaced with mini-computers for complex image analysis. However, the success of this technique depends on correct interpretation of thermal images.

A number of heatings were successfully detected by CANMET researchers using the infrared technique. [1985] In almost all cases routine visual inspections did not indicate anything abnormal. For the location of hot spots in coal stacks and in coal outcrop areas, infrared scanners proved particularly useful. Figure 4 shows some of the actual photographs of hot spots located during thermal surveys in Canadian coal operations and on coal stockpiles.

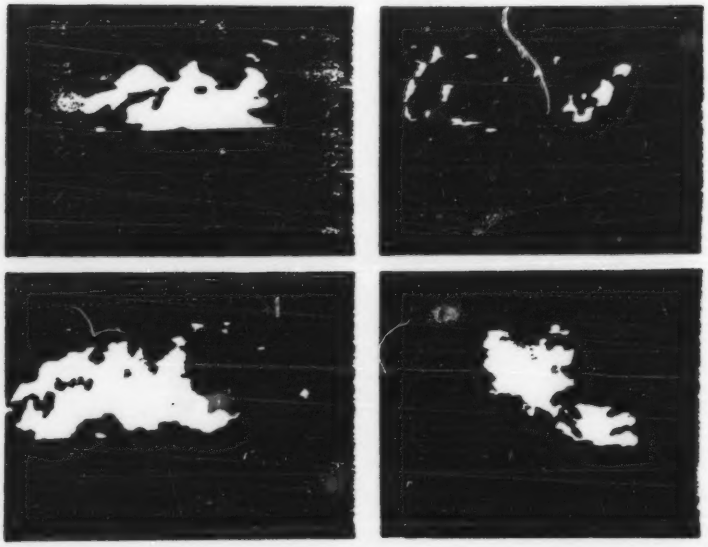


Fig. 4 - Photograph of hot spots located during thermal survey in coal outcrop area and in coal stockpiles.

ADVANCES IN SPONTANEOUS COMBUSTION SENSORS

New instruments for the measurement of the products of combustion are now available. Wood [1984] revieved briefly the instruments developed and currently used in the U.K. and their possible application in mining operations.

Electrochemical cells for the early detection of combustion products were developed in seventies, and are being used extensively worldwide for the measurement of carbon monoxide and other combustion products. A gas permeable polymer based membrane allows diffusion of carbon monoxide to a sensing electrode where it is oxidized to carbon dioxide. The two electrodes are connected via an external load which allows electrons to flow to a cathode where the oxygen is reduced.

The electrochemical cell is normally used to measure up to 500 ppm CO although equipment does exist for the detection of higher concentrations. Instruments with range of 0 - 1000 ppm CO are considered adequate for early detection of spontaneous combustion.

Semiconductor sensors which are also used for the detection of spontaneous combustion consist of a metal oxide, usually tin or zinc, where oxygen has been adsorbed in the oxide surface as negative ions. Carbon monoxide and hydrocarbons neutralizes the oxygen ions and allows oxygen to be donated to the oxide lattice and hence increase its conductivity. This increase indicates the concentration level of gases present.

Semiconductors have been found to operate accurately and satisfactorily over a long period without recalibration and with minimum maintenance problems. Sensors based on the semiconductor principle are commonly used for both fixed monitoring and with portable CO measuring devices.

A more recent development in the U.K. includes both the electrochemical cell and the semiconductor sensors in the same housing. This equipment is more versatile and allows for detection of both spontaneous combustion and local fires. Another new development is COSEC (carbon monoxide self transmitting electrochemical cell). It is robust, has a life of about eighteen months, and most importantly, does not require an outside power source to operate. This type of self powered sensor is likely to have wide applications in remote parts of the mine where there is no power supply, but can easily be installed using twin core cables.

Recently, a heat sensor has been developed in the U.K. to measure heat sources or fires based on the principle of measuring the changes in thermal noise caused by the presence of heat upstream. With these sensors a marked change can be noticed for a small addition of heat. This change is detectable long before there is any measurable change in ambient temperature. Thermal noise decays with distance and as such sensors must be located very close to the heat source. These sensors can be applied to specific underground locations particularly at transfer points where there is a risk of heating.

In addition to CO, CO_2 and other hydrocarbon gases, large quantities of submicron particles are produced during the combustion process. Litton [1979] in a recent U.S.B.M. report concludes that carbon monoxide and submicron particulate monitors offer the greatest potential for use as fire detectors in mining environments.

Particulate fire warning systems are designed to detect either visible or non-visible particles. Optical and ionization type detectors are

common. Research is being continued to make these devices insensitive to ambient dust and extreme temperature and humidity so that they may be used successfully for early detection of heating under actual mining conditions.

SELF HEATING IN COAL STACKS

There is a relatively high frequency of spontaneous combustion during storage and transportation of thermal coal. The signs of heating in these stacks is usually noticed within a period of 10-12 weeks. There are instances where heating caused by spontaneous combustion had taken place within a period of only 4-6 weeks.

The self heating phenomenon in a coal stockpile is no different than that which is observed during mining. An environment for heat accumulation is essential for spontaneous combustion to occur. Even with low rank coals the possibility of spontaneous combustion will be negligible where the coal is spread out, or the height of the stack is kept low. Although the initial oxidation of a freshly exposed coal surface is very rapid it generally declines with time. If there is no heating in the first few months the risk will be considerably reduced, provided the stack remains undisturbed.

It is essential for the safe storage of coals that there should be either adequate ventilation, or almost complete elimination of airflow through the coal stack. Storage with ventilation is recommended only for lump coal. It is obvious that there will be no control over slacking in a coal stock pile. Thus, over a period of time this is likely to restrict airflows and eventually cause heating.

The most satisfactory method for safe storage of coal is to have well compacted heaps. Care should be taken to avoid segregation - particularly lumps rolling down the sides of a coal pile. The sides should be thoroughly consolidated and hollows at the top should be avoided.

Spraying of road tar provides an effective seal to air leakage and is recommended for coal stacks which are likely to be left standing for a long time. Road tar also helps in preventing channels caused by rain. Surfactants of organic binders that are normally used for dust control are also quite effective in reducing spontaneous combustion in coal stacks.

Storing coal in vertical bunkers or coal silos are a common practice at mine sites. Such bunkers or silos reduce air leakage to some extent.

The risk of spontaneous heating could be further reduced by blanketing the coal with nitrogen. Artificial aging and treating the coal with carbon dioxide can also reduce the risk of spontaneous combustion. Commercial application of these techniques needs careful evaluation.

INERTIZATION

Major advances have been made in recent years towards the control of spontaneous combustion with the use of inert gases. The objective of inertization is to reduce the concentration of oxygen in the atmosphere. In order to ensure prevention of spontaneous combustion it is necessary to reduce the oxygen content to below 3% volume.

During the mining of coal seams which are prone to spontaneous combustion, it is possible to limit ambient temperature oxidation inside the gob without causing any hindrance to the mining process. This can be done by continuously injecting nitrogen at a slow rate in the gob area and by ensuring that the leakage path into the gate roads are minimized. In most situations the amount of nitrogen being used is well below 100 m^3/min. This technique has been used in French mines as discussed by Froger [1985] with considerable success. In the event of a fire outbreak the fire zone can be stopped off and nitrogen discharged into the area. Typically, the intake side is stopped off first and flow of nitrogen is regulated to compensate for the reduced air flow. As the airflow is gradually restricted because of the fire stopping, the nitrogen flow is increased keeping the ventilation as stable as possible. One of the essential conditions for the successful application of nitrogen is that it should be applied quickly. In Germany, it is common to have inertization plants at the mine site which enables them to apply nitrogen to a fire area at a very short notice, and often within four to twelve hours after detection. Many fires have been successfully controlled/fought using the inertization technique with nitrogen in German mines as discussed by Kock and Linberg [1985].

Most mines in France are equipped with facilities that can implement the nitrogen inertization with minimum of delay. These facilities include all the necessary connections for a nitrogen tank and portable evaporator. In many mining operations prior agreement exists with nitrogen manufacturers to promptly deliver the tank and the evaporator when required.

Collieries in the Lorraine Basin, France are connected to an industrial nitrogen supply network to reduce costs.

Carbon dioxide may be used instead of nitrogen, and sometimes in preference to nitrogen, for the purpose of inertization. Carbon dioxide because of its higher density than air is particularly suitable in situations where the location of the heating is at the bottom of a steeply sloping area, or at the bottom of a shaft.

In recent years in Canada a number of heating and fires occurred in coal silos due to the outbreak of spontaneous combustion. Most of these fires have occurred when storing partially dried thermal coal. As a result a number of mine operators in Western Canada have made provision for a supply of carbon dioxide close to the silos where coal is stored. During the last three or four years a number of heatings were successfully controlled and extinguished by inerting the silos as soon as any signs of heating were identified from gas analysis results.

Generating an inert gas at the mine site is usually cheaper than obtaining a supply of carbon dioxide or nitrogen. In this way it is also possible to produce gases at a greater flow rate. However, some disadvantages associated with this method often discourage the use of these generators. These disadvantages include (i) the need for a large volume of cooling water, (ii) non-compliance with flame proof requirements (iii) difficulty in controlling rate of generation and delivery and (iv) the need to locate the generator close to a fire because of low delivery pressures.

The design and the method of using inert gas generators are still being improved. For example, generators are being designed to use nitrogen for evaporative cooling. This increases the proportion of nitrogen in the product and enables the delivery duct to be purged before the generator is put into operation.

The subject of inertization has been discussed in detail in a recent CANMET report [1984].

DEVELOPMENTS IN SEALANT TECHNOLOGY

Recent developments in sealant technology have led to considerable improvements in the control of spontaneous combustion. This is achieved by using the sealants in areas where the ventilation airflow can filter though fissured coal. Stoppings and gateroad packs are prime examples of where sealants can be used effectively to prevent ventilation through the gob, rib pillars and worked out areas.

Sealants can be grouped into three main categories: gypsum based, cement based and others. The last group includes sealants incorporating rubber, latex, urea formaldehyde, phenolic resins and bentonite.

Gypsum based sealants usually have additives such as perlite, vermiculite, granulated mineral wool or fiberglass which helps to increase their strength and elasticity. Gypsum based sealants are also of low density and harden rapidly after application. These properties make this type of sealant particularly suitable for providing a thin airtight seal to the surface walls and roof of mine roadways. The low density prevents stressing the surface material of the mine walls and hence reduces the possibility of spalling. The additives used to increase elasticity allows for moderate strata settlement. Due to the rapid setting rate the sealant can be built-up to span gaps, fissures and cracks. In many applications the setting is too fast and additives are included to extend the natural setting time which is about 20 minutes.

The material used for cement based sealants are the same as those normally used in the construction industry such as portland, hi-magnesia, oxy-sulphate etc. The properties and uses of these sealants vary from very elastic coatings which are used as fire retardants to concrete compositions used for structural support. Both cement and gypsum can be used with foaming agents for application as a filler.

Latex sealants have only been used on a limited basis since they are difficult to store for any length of time, and the surface to be sprayed usually has to be prepared in advance of the two applications that are necessary. Their main advantage is that the sealant will remain airtight while the strata settles.

Urea-formaldehyde foam products have been developed to supercede polyurethene foams that were toxic and flammable. This foam is suitable for

filling between and under chocks or between shuttering and the side of the pack. The foam sets in 24 hours and becomes increasingly impermeable under pressure from the strata. Suspected long-term health problems have restricted its use in some regions, but where it has been used has shown that it is more cost effective than many other traditional methods.

Phenolic resins were also developed to supercede polyurethene foams. One example of this type of foam consists of a mixture of formo-phenolic resins in a water solution. When mixed with a catalyzer an exothermic reaction occurs which generates an inert gas to foam the product. This foam is both inert and non-flammable.

Bentonite is a natural clay which swells to many times its original volume when mixed with water. Bentonite injection is usually used to deal with a specific area and is not normally used for general application.

The choice of a sealant to be used in any particular circumstance is dependent on economics, regulations, the situation to which it is to be applied, the types of sealants that are available and to some extent the preference of the mine operator. The subject of sealants has been discussed in detail in a recent CANMET report [1984].

METHOD BASED ON BIOTECHNOLGY

Spontaneous heating in coal silos and coal shipholds are often responsible for initiating methane explosions. Investigations have shown that an explosive concentration of methane may occur within the coal pile inspite of adequate ventilation.

In order to deal with such hazards, new methods are being researched. One such method based on biotechnology is being investigated in Canada. This method involves bringing methane oxidizing microorganisms into contact with the coal to oxidize the methane released to non-inflammable products. Research carried out elsewhere and in Canada indicate that microbiological control of methane is feasible. Bio-oxidation of methane to carbon dioxide follows the pattern shown below:

$$CH_4 + 2O_2 = CO_2 + 2H_2O$$

Methane oxidizing bacteria used in this study are aerobic that is they require molecular oxygen to oxidize methane to carbon dioxide.

Typical results of laboratory experiments carried out by the Gemini Biochemical Research Ltd. Calgary under a CANMET contract is shown in Figure 5 [1987].

Two important factors are illustrated in this data. Firstly, there is a decrease in the concentration of methane in the silo after the bacteria are added. Secondly, the amount of oxygen present in the silo is rapidly depleted to insignificant levels. Thus the biological technique has the additional benefit of inerting the voids thereby reducing the possibility of explosion. These tests further show that there will be a spin off benefit towards prevention of spontaneous combustion during storage and transportation of coal because of the lack of oxygen within the coal pile. It appears that successful application of this technology will help in controlling both methane explosions and spontaneous combustion.

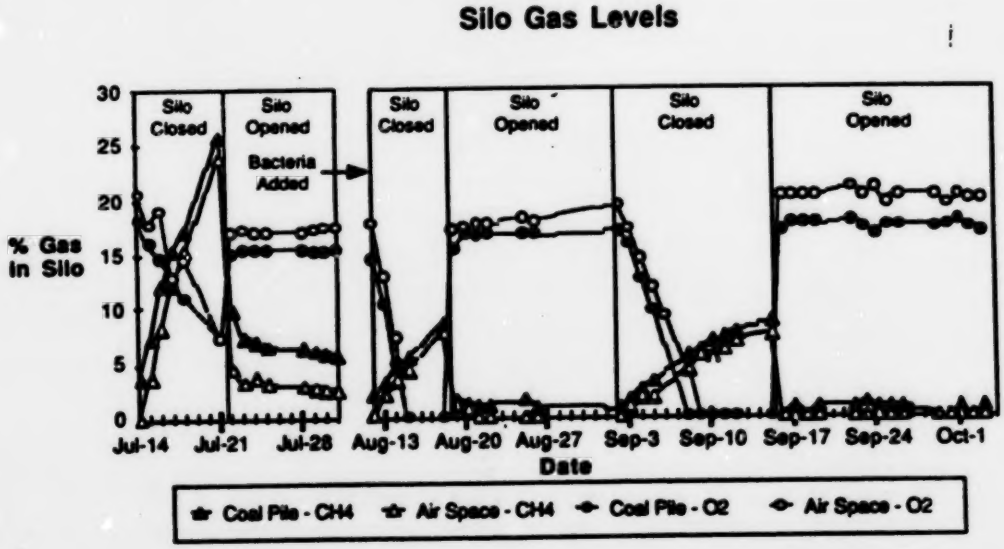


Fig. 5 - Variations in the methane and oxygen concentration in the model silo (3 tons) before and after spraying the coal with methane oxidizing bacteria.

CONCLUSIONS

An early warning system is considered the most effective tool for the prevention and control of hazards caused by spontaneous combustion. A combination of infrared thermography and continuous monitoring of carbon monoxide is able to provide adequate warning before it is too late to gain control over such heatings. Early detection should therefore form an integral part of mine planning from the development stage throughout the life of the mine.

Use of sealants to prevent air leakage should be practiced more extensively particularly in mines prone to spontaneous heating. This measure is likely to reduce the occurrence of spontaneous combustion significantly.

Inertization techniques have proved valuable in controlling the onset of spontaneous heating in gob areas and in coal storage silos. All coal mines should consider suitable emergency planning including a supply of inert gas so that once a heating is detected it can be dealt without delay.

Techniques discussed in the paper should be used as a supplement to prevent hazards associated with spontaneous combustion and not as a substitute for good mining practice.

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